

APPLICATION OF LONG FLASHOVER ARRESTERS FOR IMPROVEMENT OF LIGHTNING PROTECTION AND OPERATING VOLTAGE RELIABILITY OF DISTRIBUTION LINES

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SUMMARY

A new simple, effective and inexpensive method for lightning protection of overhead distribution lines is presented. The method suggested is a simplified discharge circuit which consists of a long surface flashover discharge element, called Long Flashover Arrester (LFA), with a length big enough to prevent Power Arc Follow (PAF). One of the most effective applications of the LFA is an insulation tube covering the line conductor. Its application improves the line reliability because it increases the main insulation of the line between the line conductor and the structure.

THE NEED TO ENHANCE THE RELIABILITY PERFORMANCE OF DISTRIBUTION POWER LINES

Distribution power lines are most common. According to information provided by the Lenenergo (St. Petersburg Power Administration), the total length of 6-10 kV overhead lines in service in the Russian Federation exceeds 1200 thousand kilometers, 698 thousand km of which (including 450 km in the Lenenergo grid alone) must be replaced or uprated. Power supply reliability is very much a function of the reliability performance of 6-10 kV overhead lines.

For a number of reasons the reliability performance of 6-10 kV overhead lines remains low. Because a majority of loads are supplied by 6-35 kV lines whose reliability is below that of higher voltage lines distribution grids account for a large percentage of power supply interruptions, both in terms of incidence and duration. This holds true both for Russia and other countries. For example, 11 to 33 kV overhead lines in Japan account for 88% of total supply interruptions and 77% of total line outages for lines of all voltage ratings [1]; 2 to 33 kV lines in UK are responsible for 77% of supply interruptions [2].

In Russia some 30 to 50% of line outages stem from mechanic causes (falling towers, conductors broken by wind or ice, vandalism etc.), while some 50 to 70% are due to electrical causes including:

- insulation flashovers and power arc onset at lightning overvoltages
- insulation flashovers at switching and quasi-stationary overvoltages

- operating voltage insulation flashovers due to pollution and wetting
- lightning impulse puncture of insulators
- insulator failures due to power arc
- conductor burn down due to power arc
- other electrical causes.

A low reliability level of 6-10 kV lines results in high undersupply penalties, as well as in a considerable increase of maintenance costs.

Among objective causes of a poor reliability performance of 6-10 kV lines one should point out a fairly low impulse strength of line insulation. For lines with reinforced concrete poles it is around 130-150 kV. Thus each lightning stroke on or near such a line of a conventional design that results in a lightning overvoltage in excess of 150 kV causes a flashover. There is also a heavy probability of a steady power arc, which brings about quasi-stationary overvoltages and equipment damage and necessitates disconnection of the line and thus load shedding.

Unless special lightning protection steps are taken to overhead lines with covered conductors, a lightning overvoltage leads first to a flashover of a line insulator and next to a breakdown of the solid conductor insulation. With a high probability such a lightning flashover brings about a power frequency arc which keeps burning at the insulation breakdown point until the line is disconnected. The arc can easily burn the insulating covering and, with heavy fault currents, melt the conductor [3].

A subjective reason is that utilities resigned themselves to an "inherently low" lightning performance of 6-10 kV lines.

The above brief analysis shows that it highly imperative to enhance the reliability performance of 6-10 kV lines. Their operational reliability can be improved many times over through ruling out or reducing radically the percentage of outages due to electrical causes. To achieve this, it is necessary to assure a high lightning performance of such lines and to make the line insulation less vulnerable to other electrical stresses. These two objectives are attained simultaneously by providing line conductors at the insulators with Long Flashover Arresters in the form of Insulation Tubes (LFA - IT) with appropriate geometrical and electrical characteristics [4].

THE LFA PRINCIPLE

When a lightning surge gets to an insulator, the insulator may flash over depending on the overvoltage value and insulation level of the line.

Probability of PAF depends on many parameters: nominal voltage of the line U_{nom} , length of the flashover path L , moment at which lightning stroke occurred, lightning current magnitude, line parameters, etc.

Many efforts have been made by different laboratories around the world to study this problem (A list consisting 14 references is presented in [5]). It was found that the main factor, which determines the probability of PAF, is the mean gradient of operational voltage along the flashover path

$$E = U_{ph}/L$$

where $U_{ph} = U_{nom} / \sqrt{3}$ = phase voltage, kV;
 L = length of flashover, m.

The probability of PAF sharply decreases with a decrease in E . An analysis of available data on sparkover discharge transition to PAF concluded that for $E=7$ to 10 kV/m probability of PAF is practically zero.

The flashover length, L is greater for lines with wooden structures rather than steel or concrete structures, because a wooden crossarm increases the flashover path. As a result probability of PAF for wooden structures is sufficiently lower than for steel or concrete supports.

From the short analysis presented above, it is clear that it is possible to improve the protection against lightning by increasing the length of lightning flashover path.

The suggested LFA accomplishes this principle. The LFA's length may be several times greater than that of an insulator (string, etc.). Due to a special inner structure the LFA impulse flashover voltage is lower than that of the insulator and when subjected to lightning overvoltage the LFA will flashover before the insulator. Due to the LFA's length there is no PAF.

THE LFA DESIGNS

Various LFA applications are described in [5]. Presented below are two of the most practical designs.

The LFA-Insulation Tube (LFA-IT)

Fig. 1 shows an application of the LFA as an insulation tube covering the line conductor.

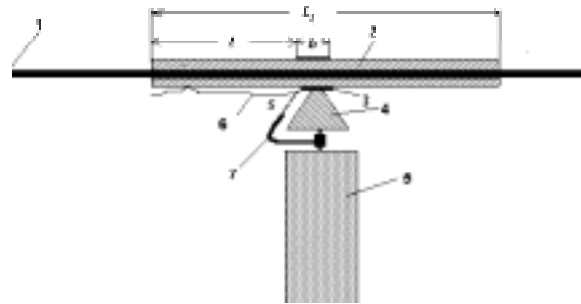


Figure 1 Long Flashover Arrester in a form of an insulation tube with a sparkover "horn".
 1- power line conductor; 2- insulation tube;
 3- metal tube clamp; 4- insulator; 5- structure;
 6- flashover channel; 7- sparkover horn;
 S- sparkover gap

Under overvoltage conditions first sparkover gap S flashes over and then a discharge channel travels along the tube until it reaches the line conductor. This LFA application is very simple. The arrester consists only of an insulation tube and a sparkover horn. The insulation tube must be made of an atmospheric exposure-resistant material and have an adequate impulse strength.

Sparkover horns are necessary for insuring flashovers of LFA-Insulation Tubes placed at different supports (please see Application Guidelines section below). Besides the sparkover horns protect the line insulators from lightning overvoltages and PAF currents.

When any apparatus, e.g. metal oxide arresters, are mounted in large numbers in parallel with line insulators the operating reliability performance of an overhead line is inevitably lowered owing to possible failures of the added devices.

Unlike this general case, installation of LFA insulation tubes, far from lowering the operational reliability of the line, improves its reliability performance under both normal operating conditions and any electrical stresses owing to an enhanced strength of the line's major insulation.

With an adequately selected thickness of its wall the insulation tube can equally well withstand the total operating voltage and all switching and quasi-stationary overvoltages. Actually LFAs assure a double back-up of the line's major insulation eliminating thereby all electrical causes of 6-10 kV line outages listed in Section 1

As shown by LFA tests reported in [5,6], a 10 kV arrester performs efficiently with a total flashover length of $L=80$ cm.

A conductor lightning overvoltage forms a spark channel on the surface of the tube and between the sparkover horns (Fig. 1). Here the length of each of the insulation tube arms is found from the relationship: $l = L - S$, where l is the flashover length over the tube surface; L , is the necessary total flashover length; S , is the sparkover gap.

The total length of the insulation tube is determined by the equation: $L_t = 2l + b$, where b is the length of the metal tube clamp on the surface of the insulation tube. L_t is equal to about 150-170 cm.

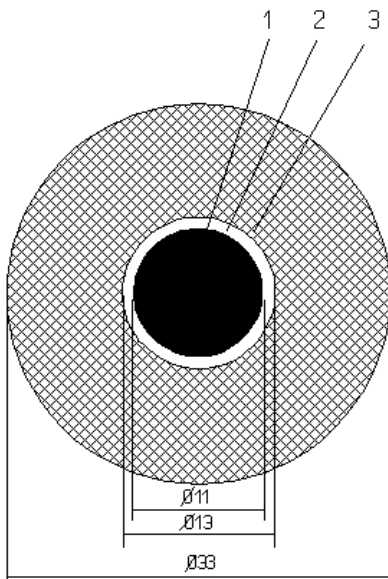


Figure 2: LFA-Insulation Tube cross-section
1 – conductor; 2 – air gap; 3 – polymeric insulation material.

By way of example Fig. 2 gives a cross-sectional view of the insulation tube mounted on the A70 aluminium conductor of a 10 kV overhead line.

The inner diameter of the tube is 13 mm, i. e. 2 mm larger than the diameter of the conductor (11 mm). Thus there is a 1 mm air gap between the inside of the insulation tube and the conductor permitting the tube to move easily along the conductor during installation.

As demonstrated by tests [5 through 8], an 8 to 10 mm thickness of the tube wall assures the needed breakdown strength for withstanding all electrical stresses, including those associated with direct lightning strokes on the conductor. For example, with a 9 mm wall thickness no breakdowns of the tube were observed at 6.2 MV impulses [8].

During stringing a conductor length equal to the length of the span between dead-end supports is unwound from the reel and threaded through insulation tubes whose number corresponds to that of supports in the anchor span. As the conductor is laid along the span the tubes are shifted to come against respective supports. After the conductor with the tubes is raised to a support it is secured to the insulator by a wire clamp exactly like in the case of conventional conductors.

Also insulation tubes could be placed on the conductor by the conductor manufacturer at intervals approximately equal to a span length. The sleeves should move freely along the conductor and must be fixed at the insulators during the line installation.

The LFA-Insulation Tubes are suitable for new overhead distributions lines under construction or for lines which should be updated because the tubes must be installed by an end of the conductor. For overhead lines which are already in operation another LFA application in a Loop form (LFA-L) could be recommended. The LFA-L could be easily installed at a distribution line and effectively protect the overhead line from induced lightning overvoltages.

The LFA – Loop

Figure 3 presents an LFA installed on a distribution pole. A piece of a steel rod covered with insulation is bent in a loop and connected to the pole with a clamp. A metallic

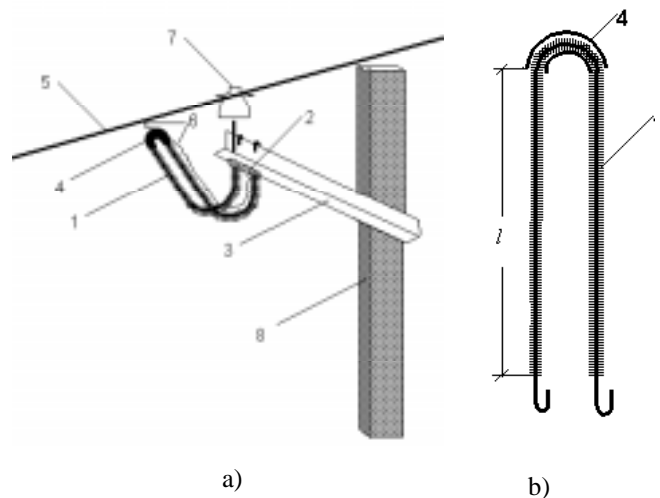


Figure 3: Long Flashover Arrester in a form of a loop installed on a distribution line cross-arm
a) Distribution Line,
b) Long Flashover Arrester
1 – insulated steel loop; 2 – clamp;
3- steel cross-arm; 4 – metallic tube,
5 – power line conductor;
6 – flashover channel; 7 – insulator;
8 – structure.

tube is placed over the insulated loop in its middle part. The metallic tube forms with the line conductor a sparkover air gap, S .

The loop is at the same potential as the pole. Due to a relatively large capacitance between the metallic tube and the metallic loop the tube is practically at the same potential as the pole. Therefore an overvoltage which appears between the line conductor and the pole will be also applied between the metallic tube and the line conductor. If the overvoltage is large enough, the gap S will be sparkover and the overvoltage will be applied between the metallic tube and the insulated loop to its insulation.

Due to the overvoltage a surface flashover develops from the metallic tube to one or both ends of the insulated loop and then to the pole thus completing the discharge circuit.

FLASHOVER CHARACTERISTICS

LFA-Insulation Tube

LFA-IT prototype for 10 kV distribution lines was built in accordance with Fig. 1.

The diameter of the conductor was 9 mm and the tube wall thickness was 8 mm. The flashover length of the line insulator was 17 cm (without sparkover horns) and the flashover length of the LFA-IT prototype was $l=75$ cm. The air gap S varied from 0 to 17 cm. The LFA was tested by 1.2/50 μ s lightning impulses of positive and negative polarity. Test impulse was applied to the conductor while the pole was grounded (Please note that after the gap is sparked over gap, the polarity of metal tube clamp which is placed in the middle of the insulated tube becomes opposite to that of the conductor). Test results are presented in Table 1.

Table 1. LFA-IT lightning impulse flashover voltages

Sparkover gap S , cm	50% flashover voltages, $U_{50\%}$, kV	
	positive polarity	negative polarity
0 (the insulator is shunted)	112	170
5	150	175
17 (without sparkover horns)	310	215

Table 1 shows that flashover voltages of the insulation with sparkover gap $S=5$ cm are considerably lower than those without sparkover horns. Therefore by application of sparkover horns it is possible to control the place of overhead line insulation flashover (please see Application Guidelines section).

In order to estimate LFA-IT performance under switching overvoltage impulses or at power frequency voltage one can use results for LFA-L prototype which are presented below. These tests have shown that LFA-IT will not be flashed over at switching overvoltages or at operational voltage even when the insulator is damaged (e. g. punctured).

LFA-Loop

LFA-L prototype for 10 kV distribution lines was built in accordance with Figure 3. An insulated loop of 9 mm diameter wire covered by 4 mm thick polyethylene insulation was used. The flashover length over the LFA was $l=80$ cm and the air gap $S=2$ cm. The LFA was tested by lightning and switching impulses and power frequency voltage.

LFA's flashover voltages were $U_{0.5LFA}^+ = +100$ kV and $U_{0.5LFA}^- = -80$ kV for positive and negative impulse polarity, respectively.

The flashover length of the line insulator was 17 cm and its flashover voltages were $U_{0.5ins}^+ = +120$ kV and $U_{0.5ins}^- = -140$ kV. In the voltage range from $U_{0.5LFA}$ to 400 kV the LFA flashed over. For impulses greater than 400 kV (U_{limit})- the line insulator flashes over. It means that the LFA-L's voltage - time curve is steeper than that of an insulator and they cross at a value U_{limit} . Therefore the LFA-L is able to protect a power line against lightning overvoltages within U_{limit} . Indeed, for distribution lines majority of induced overvoltages are in the above mentioned range. For cases of larger lightning overvoltages, for example those due to a direct lightning stroke, the line insulator will flash over first, thus protecting LFA-L from being destroyed.

Some tests were performed for polluted and wet LFA's surface. Surface conductivity was approximately 10 μ S. LFA's impulse flashover voltages practically do not depend on pollution.

For generating switching impulses a test transformer was used. The transformer was switched on by a thyristor key. A switching impulse was oscillating with time front 3000 μ s and duration (up to half-value) 7000 μ s. Amplitude of the second half period was 15% less than of the first.

For clean and dry surface of the LFA, the air gap S flashed over at a 30 kV voltage amplitude. At higher voltages, approximately 45 to 50 kV, some uncompleted surface discharge channels developed. The LFA sample withstood twenty 60 kV impulses without flashover or puncture of its insulation.

For polluted and wet LFA surface (surface conductivity 10 μ S) the air gap flashed over at 21 kV and during further increase of the impulse amplitude up to 60 kV there were no surface discharges.

Switching overvoltages at 10 kV distribution lines are much below 60 kV. Hence the LFAs will not operate at switching overvoltages.

The LFA was also tested at 50 Hz power frequency voltage for polluted and wet LFA's surface. The 2 cm air gap was sparked over at 18 kV. Consequently the LFA's air gap will not break down at operational voltage of 10 kV distribution line.

POWER ARC FOLLOW (PAF) TESTS

The test circuit (see Figure 4) consisted of three impulse current generators. Lightning Impulse Generator (LIG) provided lightning impulses with crest voltages up to 220 kV and current amplitudes up to 15 kA, front time from 1 to 5 μ s and duration (time to half value) from 40 to 60 μ s. Lightning impulses were applied to the tested object via protective GAP₁. As the protective gap the LFA sample with a 1 m flashover length was used.

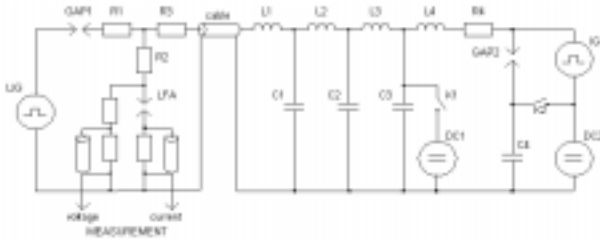


Figure 4: Power Arc Follow Test Circuit
 LIG = Lightning Impulse Generator;
 K₁, K₁ = Keys;
 DC₁, DC₂ = Direct Current Sources;
 GAP₁, GAP₂ = Air Gaps;
 IG = Triggering Impulse Generator;
 LFA = Tested LFA Sample;
 $C_1=C_2=0.1\mu F$; $C_3=300\mu F$; $C_4=1000\mu F$; $L_1=L_2=L_3=1mH$,
 $L_4=100\mu H$, $R_1=100\Omega$, $R_4=100\Omega$, R_2 and R_3 varied
 from 0 to 120 Ω .

Two generators with discharge capacitors C_3 and C_4 were used to simulate the positive and negative half-periods of the operating voltage, respectively. The second generator was applied after a time delay of 3 to 5 ms using triggering Impulse Generator (IG). Capacitors C_3 and C_4 were charged from dc current sources DC₁ and DC₂, respectively. The simulated operating voltage was applied to the LFA through a distribution line model which consisted of capacitors C_1 and C_2 , inductances L_1 , L_2 and L_3 and a 350-m long cable, simulating an overhead distribution line of approximately 6 km in length.

After application of the lightning impulse to the LFA sample, capacitor C_3 discharged through the line model forming a positive half-cycle of the operating voltage. After 3-5 ms, GAP₂ was triggered and a negative operating voltage half-cycle was applied from circuit C_4 , L_4 and R_4 .

The length of the tested LFAs varied from 0.2 to 2 m, the resistances R_2 and R_3 varied from 0 to 120 Ohms and the charging voltage U of capacitors C_3 and C_4 varied from 0 to 9 kV. During testing, U was increased in 0.5 kV steps. The highest charging voltage U at which there was no Power Arc Follow was determined as the critical voltage, U_{cr} . Thus the mean critical gradient was defined as $E_{cr} = U_{cr}/l$, where l = flashover length along the LFA.

For measuring the short-circuit current $I_{s.c.}$, the LFA was replaced by a short copper wire.

Test results including typical voltage and current oscillograms are presented in [6]. They can be approximated by a formula:

$$E_{cr} = 100(42 - 3.4U)/I_{s.c.} \quad (1)$$

where: E_{cr} = [kV/m]
 U = [kV] in the range from 0 to 9 kV
 $I_{s.c.}$ = [A] in the range from 0 to 1000A;
 all parameters are peak values.

It can be seen from equation (1) that E_{cr} depends on the short circuit current $I_{s.c.}$ and the operating voltage, U . The higher are the short circuit current $I_{s.c.}$ and the voltage U , the lower is the critical gradient E_{cr} .

APPLICATION GUIDELINES

For overhead distribution lines with insulated neutral (3-conductor ungrounded system), single-phase-to-ground short circuit currents are quite low (1 to 30 A) and PAF will be effectively prevented by LFAs.

In order to avoid high short circuit currents during two- or three-phase lightning flashovers to ground, it is reasonable to install LFAs at each pole on different phases. For example, an arrester should be installed on phase A of the first pole, on phase B of the second pole, on phase C of the third pole, etc. (see Fig. 5).

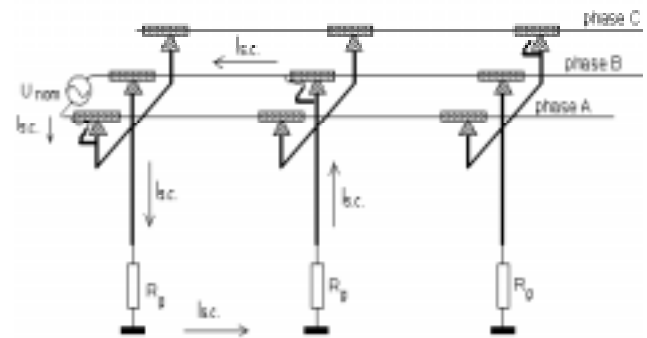


Figure 5: Sketch of LFA-Insulation Tubes installation on a distribution line

In the case of application of LFA-ITs, insulation tubes should be placed at each insulator and sparkover horns should be placed as shown in Figure 5, i. e. one horn at a pole. Flashover voltages of insulation tube with a 5 cm sparkover gap are considerably lower than those of an insulator with an insulation tube without sparkover horns (see Table 1, $S=17$ cm). Therefore at sufficiently large lightning overvoltages sparkover gaps and correspondent insulation tubes will be flashed over, while insulators with insulated tubes without sparkover gaps will withstand.

After flashover-to-ground of LFAs installed at different phases, a circuit consisting of two phases, two arresters and two grounding resistances is formed. A nominal line voltage is applied to this circuit. Both arresters are approximately in the same conditions since the current flowing through the arresters is the same.

In [6] an analysis of grounding resistance R_g influence for PAF probability P_a was carried out. Dependencies $P_a=f(R_g)$ for 6 and 10 kV distribution lines are presented in Fig. 6. The flashover length of LFA for 6 kV is $l=0.5$ m and for 10 kV line, $l=0.8$ m.

As can be seen from Fig. 6, for 6 kV line the grounding resistance which provides $P_a=0$ is $R_{g,cr}=13$ Ohm and for 10 kV line it is $R_{g,cr}=34$ Ohm. The probability of PAF increases as the grounding resistance decreases.

In a case of operation of three arresters installed at different phases, i. e. a three- phase-to-ground flashover, the phase voltage at least at one of the phases will have decreasing character. Arc quenching conditions for this phase will be most favorable. Therefore PAF will be eliminated at this phase and the regime of a three-phase-to-ground flashover will change to a two-phase-to-ground flashover.

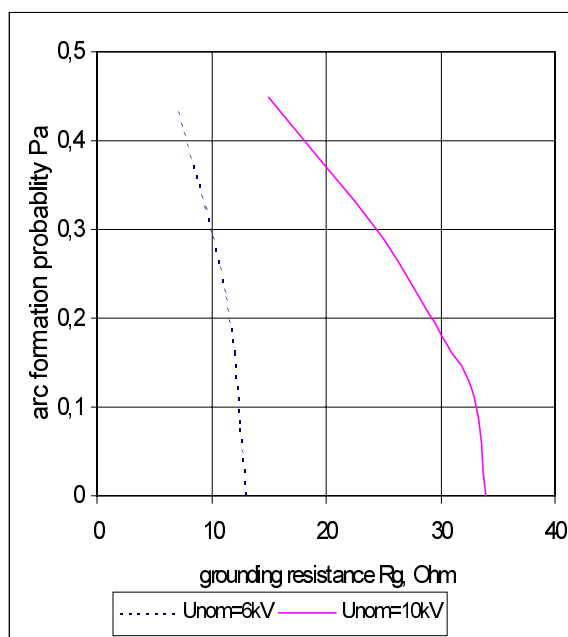


Figure 6: Probability of Power Arc Follow vs. pole grounding resistance

CONCLUSIONS

- Installation of long flashover arrester insulation tubes on 6-10 kV overhead line conductors, whether bare or covered, assures reliable lightning protection of the line both at induced overvoltages and at direct lightning strokes on the line.
- Additionally the major line insulation is strengthened considerably, which enhances the operating voltage performance of the lines.
- Line outages due to electrical causes are virtually ruled out reducing the overall line outage rate many times over, cutting drastically undersupply losses and lowering importantly the maintenance costs of utilities.
- For lightning protection of overhead distribution lines against induced overvoltages LFA-Loops are recommended.

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